A study on co- and post-seismic deformation of the 2011 Tohoku-oki earthquake inferred from GPS-acoustic observations

（別紙様式５）

論　文　内　容　要　旨

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学位論文の 題　　目	A study on co- and post-seismic deformation of the 2011 Tohoku-oki earthquake inferred from GPS-acoustic observations （GPS 音響観測に基づく 2011 年東北沖地震の地震時・地震後変動に関する研究）		

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論文内容要旨

The 2011 Tohoku-oki earthquake (the Tohoku earthquake) of magnitude of 9.0 struck the north-eastern Japan on 11 March 2011. Its co- and post-seismic crustal deformations have been measured by both the onshore and the offshore geodetic observations, and a number of the previous studies have reported the co- and post-seismic slip distributions. These studies revealed that large coseismic rupture was concentrated in the off-Miyagi region near the Japan trench, but along-trench extent of the shallow coseismic rupture has not been well constrained due to shortage of the offshore geodetic sites, which also leads a controversial issue whether the short-wavelength tsunami source excited near the trench in the off-Iwate region was caused by the shallow fault slip or not. Moreover, also due to the shortage of the offshore geodetic sites, an extensive postseismic deformation pattern of the Tohoku earthquake has not been well clarified, and then it is difficult to constrain the afterslip distribution especially near the trench.

In order to reveal the detailed co- and post-seismic slip distributions of the Tohoku earthquake, I firstly try to detect the extensive postseismic deformation field by repeated offshore geodetic observations with GPS-Acoustic (GPS-A) positioning technique utilizing a dense and wide GPS-A observation network newly constructed along the Japan trench in September 2012. Then, the co- and post-seismic slip distributions are simultaneously estimated by the slip inversion employing viscoelastic Green’s functions (the viscoelastic inversion) using the newly obtained postseismic GPS-A observation results above together with the existing co- and post-seismic geodetic observation data.

Postseismic displacement rates both in the horizontal and vertical components at each site were estimated through the GPS-A campaign observations conducted from September 2012 to September 2016. The estimated postseismic deformation field of the horizontal component shows evident spatial variation along the trench: distinct landward motions in the off-Miyagi and the northern off-Iwate regions, implying the predominance of viscoelastic relaxation; remarkable trenchward motions in the off-Fukushima and the off-Ibaraki regions, indicating rapid afterslip; and no distinct motion in the northern off-Iwate and the off-Aomori regions, suggesting insignificant contributions of the major deformation processes in the postseismic period (viscoelastic relaxation, afterslip, and fault locking). These major characteristics can be mainly interpreted by combination of the existing viscoelastic relaxation model and local afterslip, but the observation results show much larger landward motions in the southern off-Iwate region than the model. This difference suggests further contributions of the viscoelastic relaxation in this region, which may require revision of the previous coseismic slip model used in the computation of viscoelastic relaxation.

The estimated vertical motions have much larger estimation errors than those in the horizontal motions because of the trade-off nature between underwater sound speed variation and the vertical motions. Thereby, it is difficult to discuss detailed vertical postseismic deformation process from the results of a single GPS-A site. However, the obtained vertical deformation field shows clear spatial characteristics: uplift in the off-Iwate region and subsidence in the off-Miyagi region, which suggests that their regional pattern may make sense in further interpretation of the postseismic deformation processes.

Using both the co- and the post-seismic geodetic data including the above GPS-A-derived horizontal postseismic motions, the viscoelastic inversion is performed to simultaneously estimate the co- and post-seismic slip distributions. This inversion method can constrain the coseismic slip distribution not only by the coseismic displacements but also the postseismic displacements via the viscoelastic relaxation process. Due to the above GPS-A observation results in the

postseismic period, spatial resolution of the coseismic slip distribution near the trench in this study is greatly improved from the previous models derived only from the coseismic geodetic data. The estimated coseismic slip distribution demonstrates that the along-trench extent of the shallow coseismic rupture was extended further north up to 39.2° N compared with the previous models. However, this model cannot explain the short-wavelength tsunami source found in the off-Iwate region near the trench (~39.0–40.0° N). This inconsistency indicates that the tsunami source at the north of 39.2°N was caused by a mechanism other than interplate fault slip, such as submarine landslide, inelastic deformation, or subsidiary faulting. Meanwhile, along-trench variation of the shallow postseismic slip is also constrained in this study due to the GPS-A observation results near the trench. The estimated postseismic slip model clearly shows localized shallow afterslip in the off-Fukushima region.

Because spatial extents of the seismic and aseismic slip might reflect the mechanical properties on the plate interface, the estimated co- and post-seismic slip distributions in this study would provide valuable information on assessment of future seismic hazards, such as earthquake cycle simulations. Furthermore, the precisely estimated co- and post-seismic slip distributions are also useful for investigation of structural effects; for example, the aseismic slip area in this study is spatially correlated with the fluid-rich region where channel-like accretionary complexes are found. Such comparative studies are important to investigate potential of occurrence of large interplate earthquakes.

As well as examination of the co- and post-seismic slip distributions of the Tohoku earthquake, this study demonstrates advantages of the viscoelastic inversion and the spatially enhanced GPS-A observation network. Although the geodetic slip inversion has been generally performed assuming elastic media, the viscoelastic inversion has great potential for improvement coseismic slip distribution from postseismic geodetic data. Thus, it is expected that an extension (or construction) of geodetic observation network even after a mainshock plays an important role to reveal its coseismic slip behavior. The enhanced GPS-A observations provide adequate constraints on estimation of the co- and post-seismic distributions, including shallow portion of the plate interface. Furthermore, it is important to investigate the detailed spatiotemporal evolution of the slip behaviors in such an extensive region by more frequent and precise GPS-A observations in the future.

別　紙

論文審査の結果の要旨

提出された論文の目的は、海・陸の測地データを用いて、東北沖地震時変位と地震後の余効すべりを推定し、関連現象と比較することで、巨大地震発生サイクルについて言及することである。

提出者は博士前期課程から本研究に関する観測、およびそのデータ解析に取り組んできた。博士後期課程においても、観測で主導的な役割を果たし、単にデータの時系列が延長されただけではなく、多工程に渡る精度改善の工夫がみられる。また、インバージョンに組み込むまでには至らなかったが、東北大方式の GPS-A 観測形態による上下変位検出に目処を立て、明らかに有意と見られる上下変動場を示したことは、現研究がさらに発展できる可能性を示している。

本論文の手法の特徴的な点は、余効変動観測データに基づいた、「地震時すべり」と「余効すべり」の同時推定の手法を確立させたとこである。着想としては、これまで用いられてきた地震時すべりモデルから予想される粘弾性応答と、観測された余効変動が一致しない領域について、地震地すべりを修正すべきではないか、つまり「地震後」である余効変動データが「地震時」のすべりを拘束できるのではと言うものであるが、これを、粘弾性応答を通してきちんと定式化して結びつけ、一般化された形で同時推定の手法を開発し、実際に十分な解像度を有していることを実証したことは特筆すべき成果である。地震時変位を含む多くのデータが存在することが理想であるが、実際には、世界中の多くの海域で観測が手薄な状態であり、仮にそのような状態で巨大地震発生を迎えても、地震後に臨時で観測点を強化することで、地震地すべりの推定が可能なことを意味する画期的なものである。

日本海溝への適用では、既存のすべり分布が予想する粘弾性応答から外れる領域として、福島沖の余効すべりとテクトニックな解釈、三陸沖のスロースリップとの関連、地震時すべり域の北側への延長および非地震性津波源への言及等、多くの科学的成果を生み出している。

論文の一部は、すでに著名な学術誌にも掲載済みであり、研究の国際的な客観評価も得られている。また、研究を遂行する上で、国内外の研究者らとの積極的にコミュニケーションを取っており、今後研究者として自立しいく研究能力と学識はすでに備えていると判断できる。したがって、富田史章氏提出の博士論文は、博士(理学)の学位論文として合格と認める。